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# THE REPRODUCIBILITY OF TESTS ON ENERGY MANAGEMENT AND CONTROL SYSTEMS USING BUILDING EMULATORS

H.C. Peitsman

S. Wang, Ph.D.

S.H. Kärki

C. Park, Ph.D.

P. Haves, Ph.D.
*ASHRAE Member*

## ABSTRACT

*An emulator consists of a real-time simulation of a building and its HVAC system and a hardware interface that allows the simulation to be connected to a real control system. Recent studies have shown that emulation can provide a flexible and low-cost method of testing real energy management and control systems (EMCS). As part of a research project, an experiment involving four different emulators with two different EMCS was performed to study the reproducibility of the emulation method. This paper presents the results of this experiment in the form of a comparison of the predictions of energy consumption, thermal comfort, and control activity obtained from tests of the EMCS using emulators based on different design and different simulation programs.*

## INTRODUCTION

An emulator consists of a real-time simulation of a building and its HVAC system and a hardware interface that allows the simulation to be connected to a real control system. The use of emulators to assess the performance of real energy management and control systems (EMCS) has been studied in a recently completed collaborative research project (Wang et al. 1992). The work on emulation addressed hardware and software aspects of the design of building emulators and the development and verification of methods of testing EMCS performance. Design aspects are discussed by Wang et al. (1993) and a testing methodology is presented by Kelly (1993).

The research project shows that emulation is a flexible, low-cost, and convenient method for testing real EMCS. This paper addresses the question of whether the emulation method and the associated test procedures have been well enough defined to allow reproducible results to be obtained with emulators of different design. Four emulators, based on different hardware and different simulation programs, were used to test two different EMCS under three typical weather conditions (spring, summer, and winter). The results of this experiment are presented in the form of a comparison of the predictions of energy consumption, thermal comfort, and control activity produced by each emulator for each EMCS.

The intention of this exercise was to evaluate the reproducibility of four emulators. No specific attention was given to the optimization of the applied EMCS control strategies and, furthermore, no comparisons of different EMCS were performed.

## DESCRIPTION OF THE EXERCISE

### The Emulators

The validation exercise involved building emulators constructed by four of the participants in IEA Annex 17. Two of the emulators consist of a 32-bit desktop computer and plug-in I/O cards. The other two emulators consist of two desktop computers and an external data acquisition and control system (DACS). All the emulators use component-based simulation programs, TRNSYS (Klein et al. 1976) and HVACSIM + (Park et al. 1985). Further details of the emulators are presented by Wang et al. (1993).

## THE BUILDING AND HVAC SYSTEM

The simulated building is a three-story office building with a variable-air-volume (VAV) HVAC system. A single air-handling unit serves three zones, one on each floor, as illustrated in Figure 1. Each floor consists of an occupied space and a return air plenum. The air handler consists of a mixing box, a preheating coil, a cooling coil, and supply

**Henk C. Peitsman** is senior researcher at TNO Building and Construction Research, Department of Indoor Environment, Building Physics and Systems, Delft, the Netherlands. **Shengwei Wang** (formerly a senior researcher at the Laboratory of Thermodynamics, University of Liège, Belgium) is a lecturer in the Department of Building Service Engineering, Hong Kong Polytechnic, Hong Kong. **Satu Kärki** is research scientist at the Technical Research Centre of Finland, Laboratory of Heating and Ventilation, Espoo, Finland. **Cheol Park** is a mechanical engineer at the Building Environment Division, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA. **Philip Haves** is a senior lecturer in the Department of Civil Engineering, Loughborough University of Technology, UK.

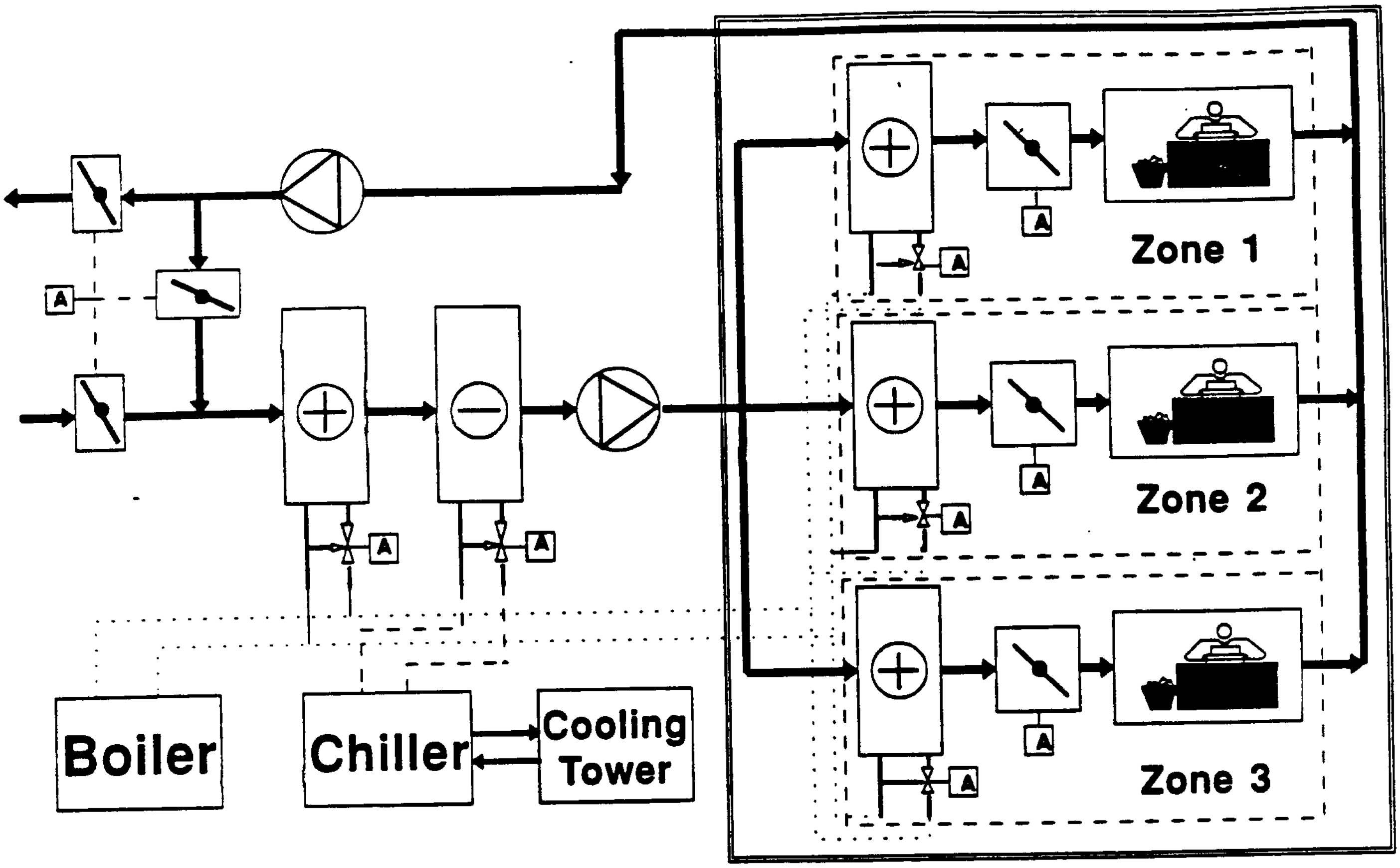


*Figure 1 Schematic of the building and HVAC system.*

and return fans. Each zone has a reheat coil and a VAV box to vary the temperature and flow rate of the air supplied to that zone.

The central plant consists of an oil-fired boiler, a reciprocating chiller, and a cooling tower. The boiler and chiller are controlled by on/off controllers. The cooling tower capacity is controlled by switching the speed of a two-speed fan and modulating the position of a three-port valve using a PI controller. The cooling tower can also operate at reduced capacity using natural convection. The central plant controllers were included in the simulation program rather than the EMCS.

Each of the four emulators used essentially the same models of the building and HVAC components. The format and structure of the component models used in HVACSIM+ and TRNSYS are very similar, facilitating the porting of component model subroutines between the two programs.

The principal dynamics of the building, heating/cooling coils, actuators, temperature sensors, chiller, and cooling tower are treated by the component models. Static models were used for the boiler, the axial fans, the mixing box, and the ducts (Wang 1992a). The control of static pressure is implemented implicitly in the simulation rather than explicitly in the EMCS. Local pressure changes were not considered in the simulation model.

The building is represented by a second-order dynamic model. The convective and radiative heat exchanges with the outside are treated by using the equivalent outdoor sol-air temperatures. The heating/cooling coils use a first-order dynamic model. For the purpose of calculating the transient response, the temperature of the metal and water in the coil is assumed to be equal to the mean surface temperature of the coil. The global heat transfer resistances on air and water sides are computed according to classical compact heat exchanger theory.

The motor-driven actuator model treats the limited speed of the motor, hysteresis, nonlinearities due to the geometry of the linkage, and the dead band of the positioner. The outputs of the model include the total movements and the number of starts, stops, and reversals of the actuator during the emulation, which are taken to provide an indication of wear and maintenance costs. The temperature sensors are modeled as having a linear, first-order response, with the time constant dependent on whether the sensor is located in a duct or in a room.

## EMCS AND THEIR CONTROL STRATEGIES

Microprocessor-based EMCS were supplied by two different manufacturers. The control strategy of EMCS 1 was implemented by the supplier according to the requirements of the exercise, whereas EMCS 2 was programmed by one of the participants (ULg). Two nominally identical sets of hardware from each manufacturer were circulated in

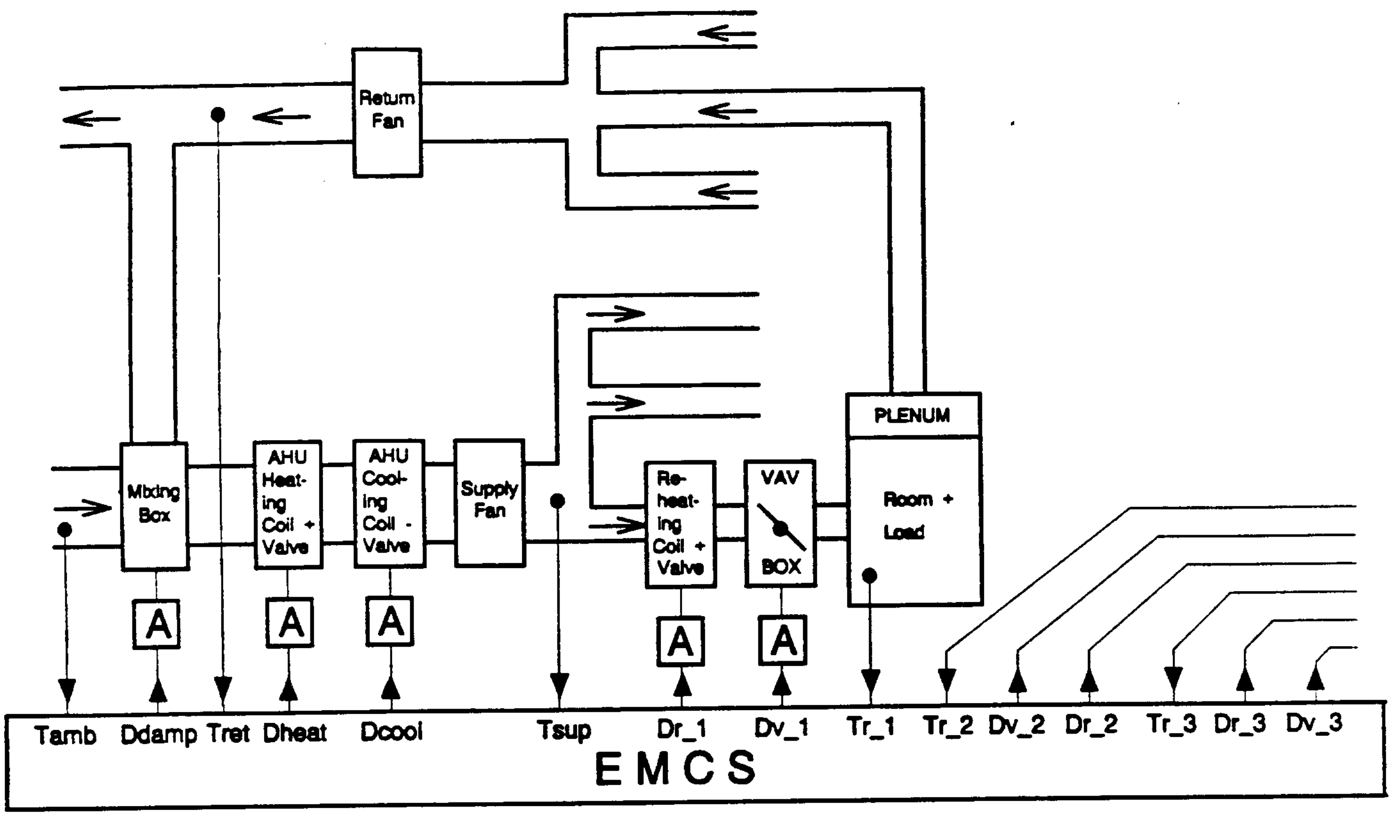


*Figure 2* *Information exchange between simulated HVAC system and the EMCS, without presentation of static pressure meassurement for VAV control.*

order to speed up the testing process. The tuning parameters for the control loops were held constant throughout the study.

The EMCS systems employed similar but not identical control strategies. In each case, the local loop control of the supply air temperature involves the sequencing of the heating and cooling coils to avoid simultaneous heating and cooling. EMCS 1 uses a form of dry-bulb economizer control of the mixing box in which the direction of movement of the dampers depends on the relative temperatures of the outside and return air. EMCS 1 employs "load analyzer" control to reset the supply air temperature so that the demanded airflow to the zone with the highest load is just less than the maximum.

EMCS 2 uses a heuristic strategy to control the mixing box and reset the supply air temperature based on the outside air temperature and the zone demands. The aim of the strategy is to maximize the use of free cooling. In each case, the local loop control of the zone air temperature involves the sequencing of the VAV box and the reheat coil.

The following outputs from simulated sensors are to be connected to the EMCS:

- ambient dry-bulb temperature,
- supply air temperature,
- return air temperature,
- zone 1 room temperature,
- zone 2 room temperature,
- zone 3 room temperature, and
- plant on/off.

The following control signals from the EMCS are to be connected to simulated actuators:

- mixing box damper demanded position,
- AHU heating coil valve position,
- AHU cooling coil valve position,
- reheat coil valve position for zone 1,
- VAV damper position for zone 1,
- reheat coil valve position for zone 2,
- VAV damper position for zone 2,
- reheat coil valve position for zone 3, and
- VAV damper position for zone 3.

Figure 2 presents the information exchange between simulated HVAC system with the EMCS to be tested.

## METEOROLOGICAL DATA AND INTERNAL LOADS

The EMCS were tested with 10-hour periods of minute-by-minute meteorological data selected to be typical of spring, summer, and "mild" winter weather in Helsinki, Finland. The equivalent outdoor sol-air temperatures for the occupied space and the ceiling plenum were calculated from the meteorological data by a preprocessor program that also

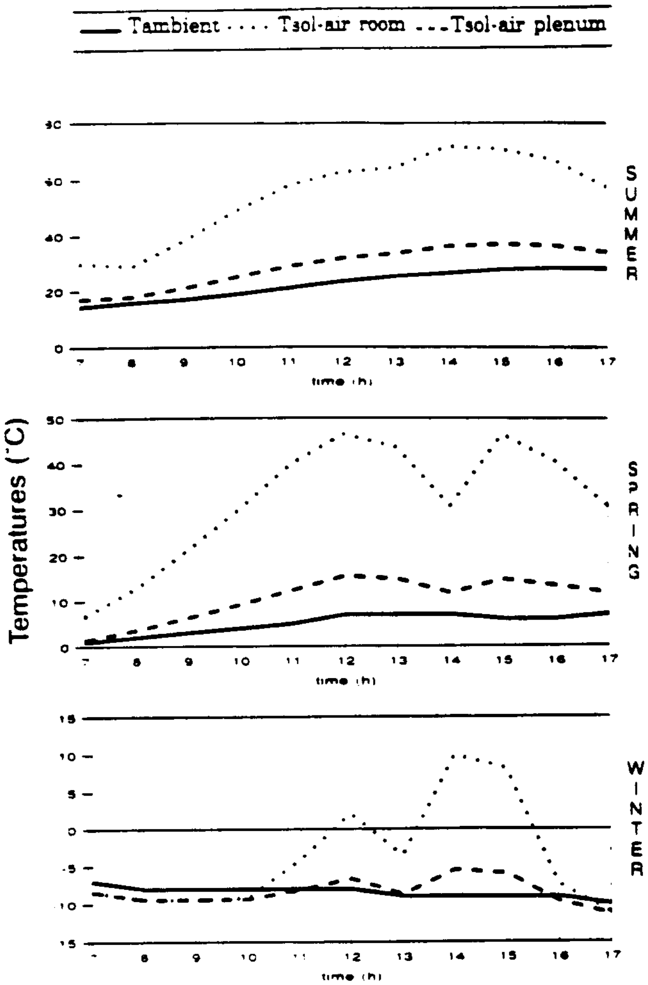


*Figure 3* *Outside air and sol-air temperatures of the three weather periods.*

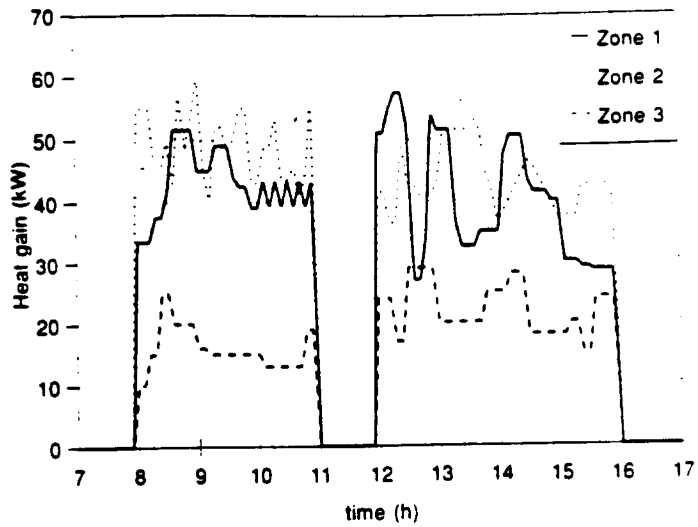


*Figure 4* *Internal heat gains of the zones.*

takes as inputs the relevant thermal properties of the zone. The ambient dry-bulb and sol-air temperatures for the three seasons are shown in Figure 3. It should be noted that any type of climate can be incorporated in emulation tests.

The internal heat gains of occupancy, equipment, and lighting used by the simulation are shown in Figure 4. The high-frequency variations provide some disturbances for the control system. The heat gains due to occupants and equipment, together with 48% of the heat gain from the lights, are added to the internal node of the occupied space. The remainder of the heat gain from the lights is added to the internal node of the ceiling plenum. The same internal heat gains were used for all three seasons.

## VERIFICATION OF THE EMCS EMULATION METHOD

### Performance Criteria

The different emulators are evaluated by comparing three measures of system performance: energy consumption, discomfort, and control activity. Control activity is taken to be an indicator of the effect of the control system on wear and maintenance costs.

**Energy Consumption** The energy consumption considered here is based on the operation of an oil-fired boiler, the chiller, the cooling tower fan, the supply, and the return fan.

**Discomfort** Fanger's predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) analyses (Fanger 1970) can be used to assess thermal discomfort. The average value of PPD over the occupancy period has been used as an indicator of the level of dissatisfaction.

**Maintenance Costs** In the absence of any empirical data on the relationship among the control activity, wear, and maintenance costs, the hourly average number of start/stops and reversals and the total distance traveled of each actuator are used as indicators of probable maintenance costs (Dexter and Trewhella 1990).

## RESULTS

As noted previously, all simulation programs for each emulator used essentially the same computer code for the models of the physical components. Each of the four participants used the same strategy and tuning values in each EMCS. Any differences in the results obtained should therefore be indicative of differences in the numerical performance of the two simulation programs or of deficiencies in the testing methodology, e.g., in the calibration procedures for the hardware interface.

Since three of the participants used the same simulation program, any difference in their results can be attributed to deficiencies in the test methodology. Differences between one partipant's results and the results of the other three may be either from differences between the simulation programs or ambiguities in the test procedures. The simulation time-step in one program is automatically adjusted by the program. Upper and lower limits of 5 seconds and 1/10

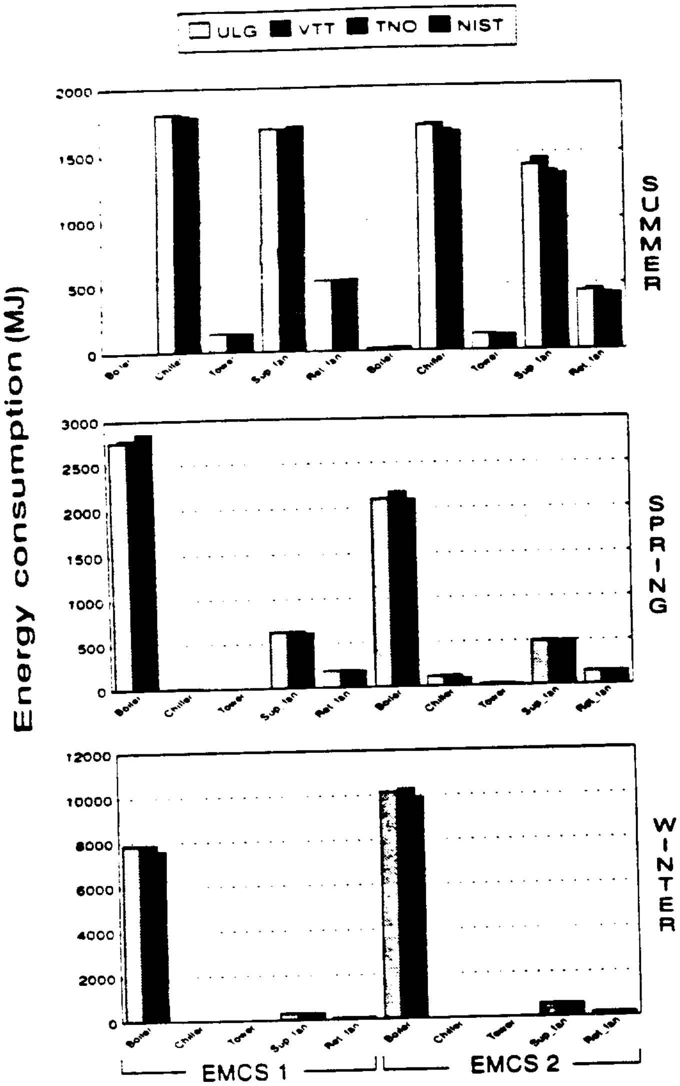


*Figure 5* *Energy consumption for the three weather periods of EMCS 1 and EMCS 2.*

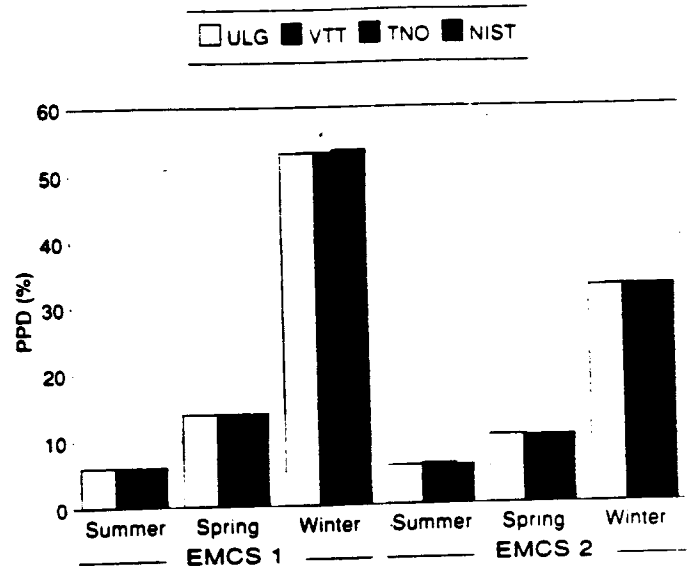


*Figure 6* *Average PPD values of EMCS 1 and EMCS 2.*

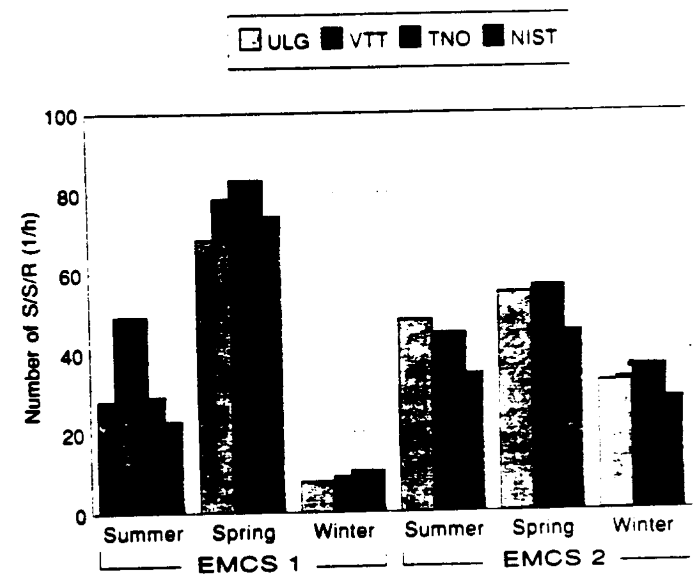


*Figure 7* *Average start/stop/reversal of EMCS 1 and EMCS 2.*

second, respectively, were employed. A fixed time-step of two seconds was used for another program.

The values of energy consumption for the different components that were obtained by using the four emulators to test the two EMCS are given in Tables 1 and 2. Average values of the discomfort and wear indicators are also presented. The discomfort indicator does not include data obtained during the first 30 minutes after the plant is switched on. Control activity is indicated by the number of starts, stops, and reversals (S/S/R) and the total distance traveled (TD) by each actuator. The column AVG gives the average value of the four results. The results are presented graphically in Figures 5 through 8.

Figure 5 shows the energy consumption of the different components. Figure 6 shows the discomfort, and Figures 7 and 8 show the control activity.

Very good agreement on energy consumption and thermal comfort is obtained for EMCS 1. However, the variation in the energy consumption results obtained for EMCS 2 is significantly greater. This is thought to be due to differences in the initial start values of the integral terms in the PI controllers at the beginning of each run. EMCS 1 has a default facility to reset the integral terms to zero automatically when it has received the start signal of the plant, whereas manual intervention is required for EMCS 2. The results of EMCS 2 are based on manual intervention at the beginning of each run.

The differences in the observed control activities (S/S/R and TD) are significant for both EMCS 1 and EMCS 2. Wang (1992b) has shown that the estimates of control activity obtained from emulators are much more sensitive to simulation time step and communication interval than integrated quantities, such as energy consumption and discomfort, as indicated by average PPD. Significant

## TABLE 1
### Energy Consumption, Discomfort, and Wear Indicators for the Three Weather Periods of EMCS 1

| EMCS 1 | | ULG | VTT | TNO | NIST | AVG | Error relative to AVG (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | ULG | VTT | TNO | NIST |
| SUMMER | Boiler (MJ) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Chiller (MJ) | 1807 | 1811 | 1802 | 1789 | 1802 | 0.28 | 0.50 | 0 | -0.72 |
| | Tower (MJ) | 138.9 | 139.1 | 139.2 | 138.0 | 138.8 | 0.07 | 0.22 | 0.29 | -0.58 |
| | Sup.fan (MJ) | 1697 | 1691 | 1695 | 1712 | 1699 | 0.12 | -0.47 | -0.24 | 0.77 |
| | Ret.fan (MJ) | 533.7 | 535.5 | 537.0 | 543.0 | 537.3 | -0.67 | -0.34 | -0.06 | 1.06 |
| | PPD (%) | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 0 | 0 | 0 | 0 |
| | S/S/R (hr$^{-1}$) | 28.0 | 49.2 | 29.3 | 23.1 | 32.4 | -13.85 | 51.85 | -9.57 | -28.7 |
| | TD (hr$^{-1}$) | 0.63 | 0.98 | 0.63 | 0.91 | 0.79 | -20.25 | 24.05 | -20.25 | 15.19 |
| SPRING | Boiler (MJ) | 2763 | 2785 | 2757 | 2853 | 2790 | -0.97 | -0.18 | -1.18 | 2.26 |
| | Chiller (MJ) | 10.2 | 10.0 | 9.9 | 0.25 | 10.0 | 1.50 | -0.40 | 1.20 | 98 |
| | Tower (MJ) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Sup.fan (MJ) | 634.7 | 629.9 | 639.3 | 623.0 | 631.7 | 0.47 | 0.29 | 1.20 | -1.38 |
| | Ret.fan (MJ) | 192.5 | 191.0 | 193.9 | 189.0 | 191.6 | 0.47 | -0.31 | 1.20 | -1.36 |
| | PPD (%) | 13.9 | 13.8 | 14.0 | 14.0 | 13.9 | 0.0 | -0.72 | 0.72 | 0.72 |
| | S/S/R (hr$^{-1}$) | 68.4 | 78.6 | 83.4 | 74.3 | 76.2 | -10.24 | 3.15 | 9.45 | -2.49 |
| | TD (hr$^{-1}$) | 1.59 | 1.75 | 1.77 | 2.28 | 1.85 | -14.05 | -5.41 | -4.32 | 23.24 |
| WINTER | Boiler (MJ) | 7877 | 7872 | 7896 | 7617 | 7816 | 0.78 | 0.72 | 1.02 | -2.55 |
| | Chiller (MJ) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Tower (MJ) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Sup.fan (MJ) | 329.5 | 328.2 | 330.3 | 326.0 | 328.5 | 0.30 | 0.09 | 0.55 | -0.76 |
| | Ret.fan (MJ) | 99.0 | 98.7 | 99.3 | 98.0 | 98.8 | 0.20 | -0.10 | 0.51 | -0.81 |
| | PPD (%) | 53.2 | 53.3 | 53.1 | 53.7 | 53.3 | -0.19 | 0 | -0.18 | 0.75 |
| | S/S/R (hr$^{-1}$) | 7.8 | 7.8 | 9.0 | 10.4 | 8.8 | -11.36 | -11.36 | 2.27 | 18.18 |
| | TD (hr$^{-1}$) | 0.47 | 0.65 | 0.63 | 0.94 | 0.67 | -29.99 | -2.99 | -5.97 | 40.3 |

## TABLE 2
### Energy Consumption, Discomfort, and Wear Indicators for the Three Weather Periods of EMCS 2

| EMCS 2 | | ULG | VTT | TNO | NIST | AVG | Error relative to AVG (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | ULG | VTT | TNO | NIST |
| SUMMER | Boiler (MJ) | 20.9 | 21.3 | 21.2 | 26.0 | 22.4 | -6.70 | -4.91 | -5.35 | 16.1 |
| | Chiller (MJ) | 1710 | 1721 | 1676 | 1659 | 1692 | 1.06 | 1.71 | -0.95 | -1.95 |
| | Tower (MJ) | 121.01 | 119.5 | 115.9 | 114.0 | 117.6 | 2.90 | 1.62 | -1.45 | -3.06 |
| | Sup.fan (MJ) | 1405 | 1454 | 1362 | 1340 | 1390 | 1.08 | 4.60 | -2.01 | -3.60 |
| | Ret.fan (MJ) | 440.5 | 457.0 | 426.6 | 419.0 | 435.8 | 1.08 | 4.87 | -2.11 | -3.86 |
| | PPD (%) | 5.95 | 5.87 | 6.17 | 5.90 | 5.97 | -0.33 | -1.68 | 3.35 | -1.17 |
| | S/S/R (hr$^{-1}$) | 48.2 | 38.4 | 44.9 | 34.8 | 41.6 | 15.9 | -7.70 | 7.93 | -16.3 |
| | TD (hr$^{-1}$) | 1.32 | 0.87 | 0.95 | 1.08 | 1.06 | 24.5 | -17.9 | -10.4 | 1.88 |
| SPRING | Boiler (MJ) | 2100 | 2104 | 2173 | 2091 | 2117 | -0.8 | -0.6 | 2.6 | -1.23 |
| | Chiller (MJ) | 111.8 | 114.8 | 119.5 | 89.0 | 108.8 | 2.8 | 5.5 | 9.8 | -18.2 |
| | Tower (MJ) | 20.1 | 20.9 | 20.7 | 11.0 | 18.2 | 10.4 | 14.8 | 13.7 | -39.6 |
| | Sup.fan (MJ) | 497.7 | 504.0 | 493.3 | 496.0 | 497.8 | -0.02 | 1.2 | -0.9 | -0.36 |
| | Ret.fan (MJ) | 150.0 | 151.9 | 148.7 | 150.0 | 150.2 | -0.13 | 1.13 | -1.0 | -0.13 |
| | PPD (%) | 10.32 | 10.20 | 9.80 | 10.30 | 10.16 | 1.58 | 0.39 | -3.54 | 1.38 |
| | S/S/R (hr$^{-1}$) | 54.9 | 45.6 | 56.6 | 45.3 | 50.6 | 8.5 | -9.88 | 11.9 | -10.5 |
| | TD (hr$^{-1}$) | 1.15 | 1.15 | 1.11 | 1.21 | 1.16 | -0.9 | -0.9 | -4.3 | 4.3 |
| WINTER | Boiler (MJ) | 10150 | 10150 | 10280 | 9909 | 10122 | 0.28 | 0.28 | 1.60 | -2.1 |
| | Chiller (MJ) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Tower (MJ) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Sup.fan (MJ) | 590.2 | 589.6 | 601.8 | 584.0 | 591.4 | -0.20 | -0.30 | 1.80 | -1.3 |
| | Ret.fan (MJ) | 178.2 | 178.0 | 181.8 | 176.0 | 178.5 | -0.17 | -0.28 | 1.85 | -1.4 |
| | PPD (%) | 32.7 | 32.8 | 32.2 | 32.8 | 32.6 | 0.31 | 0.61 | -1.22 | 0.61 |
| | S/S/R (hr$^{-1}$) | 32.4 | 33.2 | 36.4 | 28.3 | 32.6 | -0.60 | 1.84 | 11.70 | -13.2 |
| | TD (hr$^{-1}$) | 0.92 | 0.89 | 0.88 | 0.91 | 0.90 | 2.22 | -1.10 | -2.20 | 1.11 |

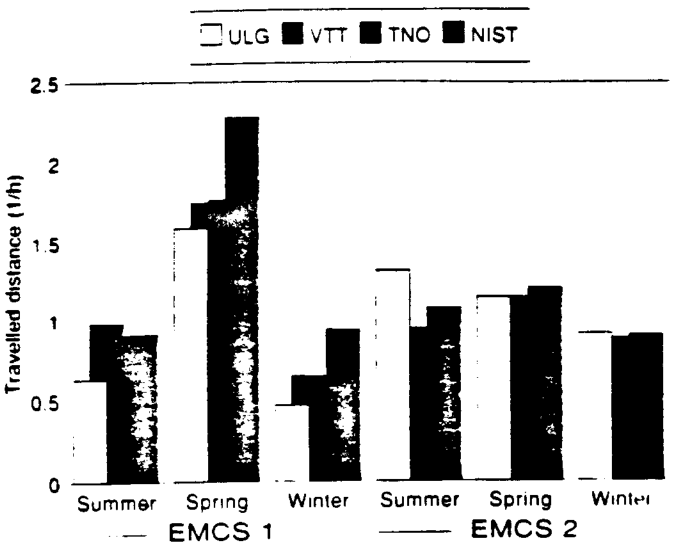


*Figure 8* *Average traveled distance of EMCS 1 and EMCS 2.*

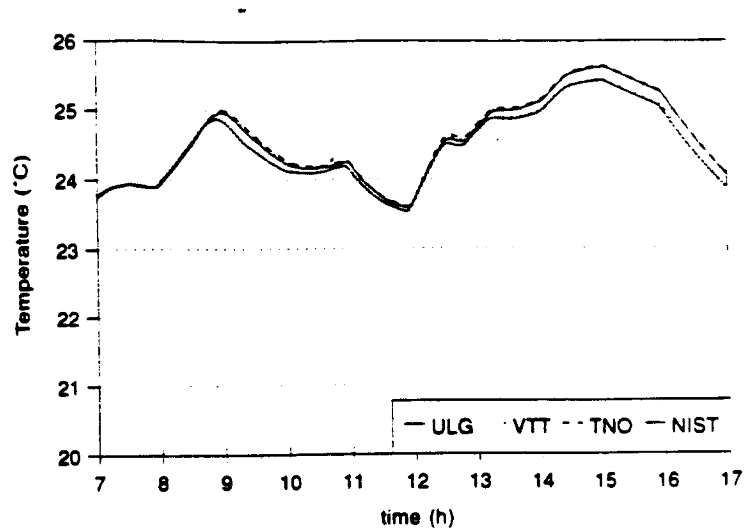


*Figure 9* *Room temperature of zone 1 of the summer exercise, EMCS 1.*

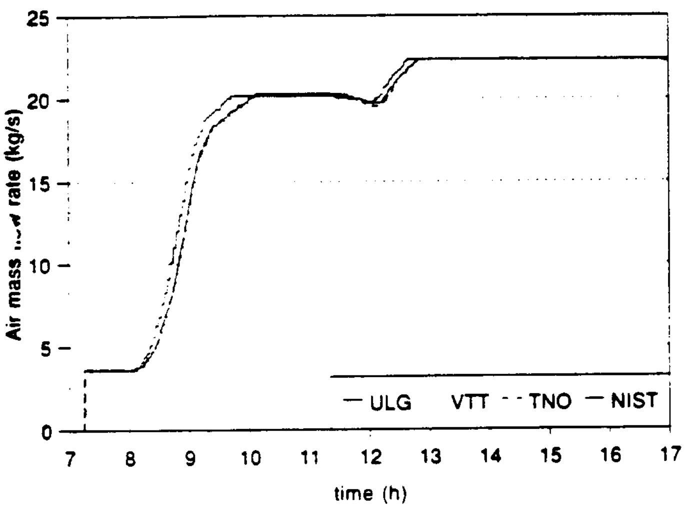


*Figure 10* *Total air mass flow rate of the three zones of the summer exercise EMCS 1.*

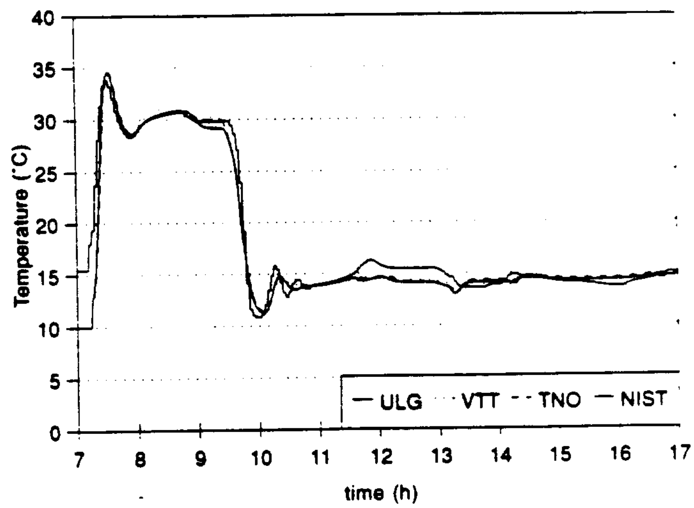


*Figure 11* *Supply air temperatures of the air-handling unit of the spring exercise, EMCS 2.*

variations in control activity are observed between the results obtained using the same simulation program (TRNSYS) running with the same time-step (two seconds). The control activity results from two participants show some apparently significant differences, even though the architecture of their emulators is very similar.

Although the purpose of this paper is to assess the reproducibility of tests of the same EMCS using different emulators operated by different personnel in different organizations, it may be noted that EMCS 2 appears to perform significantly better than EMCS 1 when there is a cooling load.

The higher fan energy consumption of EMCS 2 in the winter suggests that the higher boiler energy consumption of EMCS 2 is due to more air, and hence more outside air, being supplied to the zones when the HVAC system is controlled by EMCS 2.

The high values of the discomfort indicator (PPD) obtained during the winter indicate that the capacity of the preheat coil and/or the reheat coils is inadequate, and this conclusion is supported by a detailed analysis of the results. (The HVAC system was designed for use in the United Kingdom, whereas Finnish weather data were used in the exercise). The control activities of the actuators are greatest during the spring test period because all the actuators are active.

More results are presented in Figures 9 through 13. Figure 9 shows the temperature of zone 1 for the summer day using EMCS 1. There is good agreement with the calculated zone temperatures of the four emulators. (Differences of ≈ 0.1°C are to be expected due to errors in the calibration of the sensor channels.) Figure 10 shows the total air mass flow rate to all the zones for the summer day using EMCS 1. At the beginning of the occupancy period,

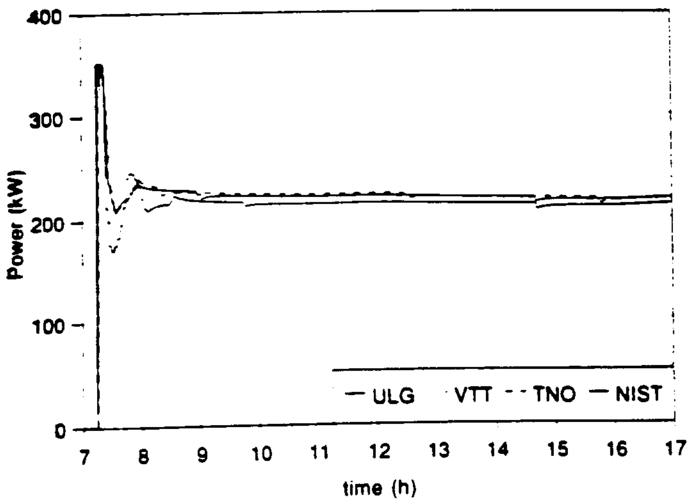


*Figure 12* *Instant power of the boiler of the winter exercise, EMCS 1.*

the zone temperatures are lower than the setpoint of 24°C (see Figure 9), and the VAV system starts with a minimum airflow rate. After 1:00 p.m., the maximum air mass flow rate is reached, indicating that the cooling load cannot be satisfied in any of the three zones. Figure 11 shows the supply air temperature for the spring day using EMCS 1. At the beginning of the occupancy period, the system is in heating mode but subsequently switches to free cooling mode. Figure 12 shows the power output of the boiler during the winter day using EMCS 1. The maximum boiler capacity is reached at the beginning of the test period.

## SUMMARY OF THE ERRORS

The errors of the energy consumption reported in Tables 1 and 2 are presented graphically in Figure 13 in terms of relative errors. A relative error is defined as

$$ABS((emulator(n)-AVG) / (0.01*MAX)),$$

where

AVG = (ULg + VTT + TNO + NIST)/4,
n = ULg, VTT, TNO, NIST.

The relative errors are expressed as a percentage of the maximum average (MAX) value of each component over all

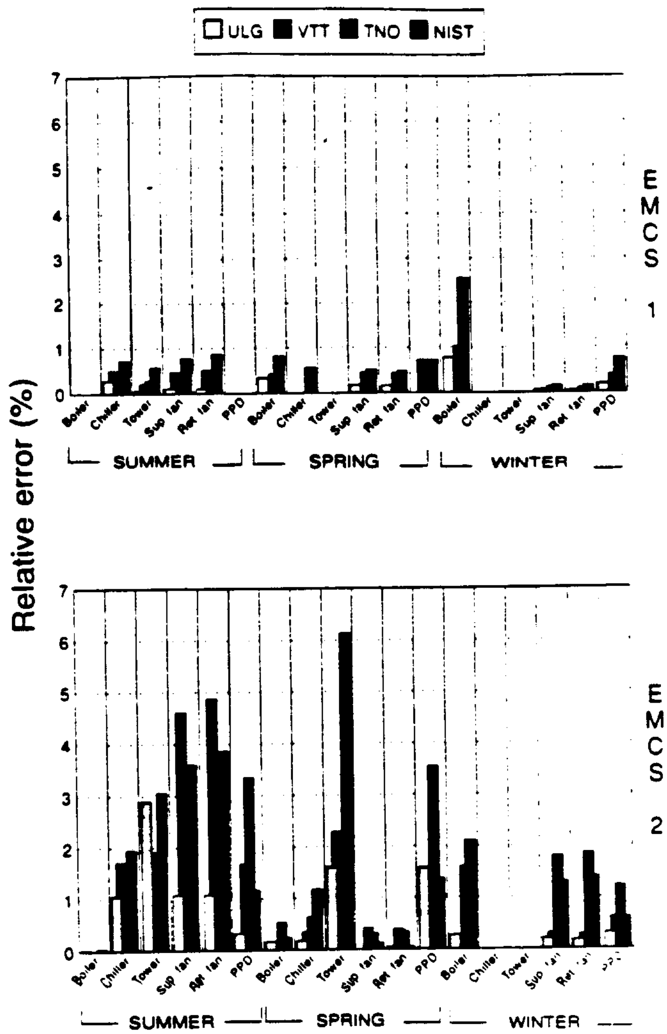


*Figure 13* *Overview of relative error of the energy consumption of each period. The relative errors are expressed as a percentage of the maximum average (MAX) energy consumption of each component over all three periods.*

three periods. The average error of all components of the four emulators with EMCS 1 is less than 1%. During the spring test day, the chiller consumption estimated by one emulator is almost zero, and the consumption estimated by the other emulators is small (≈0.5% of the chiller consumption on the summer day). A repeat of the experiment with a greater variety of test days would be expected to clarify the cause of this particular result, which may be the result of the different numerical methods employed by the two simulation programs combined with a particular threshold or other strong nonlinearity in EMCS 1. It may be noted that the same effect occurs, but to a much lesser extent, with EMCS 2. The average error of the four emulators with EMCS 2 is 3%. As suggested earlier, this increase over the error for EMCS 1 may be a result of a failure to zero the integral terms in the PI controllers. The procedure for comparative testing of EMCS should include initialization of all control loops.

## CONCLUSIONS

1. The comparisons of the tests using different emulators show that similar predictions of the performance of EMCS strategies and algorithms can be obtained using emulators based on different hardware and different simulation programs.
2. The results show that different emulators can show good agreement relative to energy consumption and thermal comfort (control quality). With careful calibration of the hardware interface, the differences in the values of energy costs and thermal comfort can be expected to be less than a few percent.
3. The test results show that order of magnitude agreement on the potential wear and maintenance cost of different EMCS and/or control strategies can be obtained using the type of emulator considered here. However, the relationship among control activity, wear, and maintenance costs of HVAC systems is poorly understood; the approximate indication of control activity provided by these emulators should be treated with caution. Further work in this area is required.
4. The variation in the results obtained from HVACSIM+ and TRNSYS is greater than the variation between the different results obtained using TRNSYS. This suggests that the choice of simulation program may influence the results of emulation tests. The differences may have arisen from the use of a variable time-step in HVACSIM+ and the question could be investigated by repeating the HVACSIM+ experiment with a fixed time step (the time step can be forced to be constant by setting the upper and lower limits to be equal). The comparison shows that the effects are generally small and do not present a fundamental problem.
5. The experience obtained in the current experiment shows that the calibration errors in the hardware interface (and in the EMCS) have a significant effect, particularly on energy consumption. A calibration error in a sensor channel is equivalent to a change in the setpoint for the corresponding control loop that is equal to the error. Errors of 5% to 10% in energy consumption can result from relying on factory calibration.
6. The initial conditions, e.g., the integral term in a PI controller, have a significant influence when an EMCS is tested over a short time period. Careful initialization is required to avoid these problems.
7. The overall experience of this experiment shows that emulation is a very convenient testing method for EMCS performance evaluation. The agreement of the test results shows that emulation can produce repeatable results and provide a reliable method of testing EMCS.

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